

APPENDIX A: PLANE WAVE PENETRATION OF REINFORCED CONCRETE

The shielding effectiveness of reinforced concrete is examined in this Appendix. Reinforced concrete is a typical wall composition and thus serves as a representative example of the level of shielding that can be expected from many buildings housing sensitive equipment. To estimate the inherent shielding due to a reinforced concrete wall, the finite-difference time-domain (FDTD) technique can be used to calculate reflection and transmission coefficients for reinforced concrete walls as a function of re-bar spacing, diameter, wall thickness, and frequency. An idealized reinforced concrete wall is characterized by its thickness W , the period of the re-bar lattice P , the re-bar diameter D , and the electrical properties of the concrete, as indicated in Figure A1. The results of this analysis are given in terms of the reflection and transmission coefficients for a normally incident plane wave. The transmission coefficient T is defined by $E_t = TE_0$ where E_0 is the incident electric field and E_t is the transmitted electric field. The reflection coefficient R is defined by $E_r = RE_0$ where E_r is the reflected electric field.

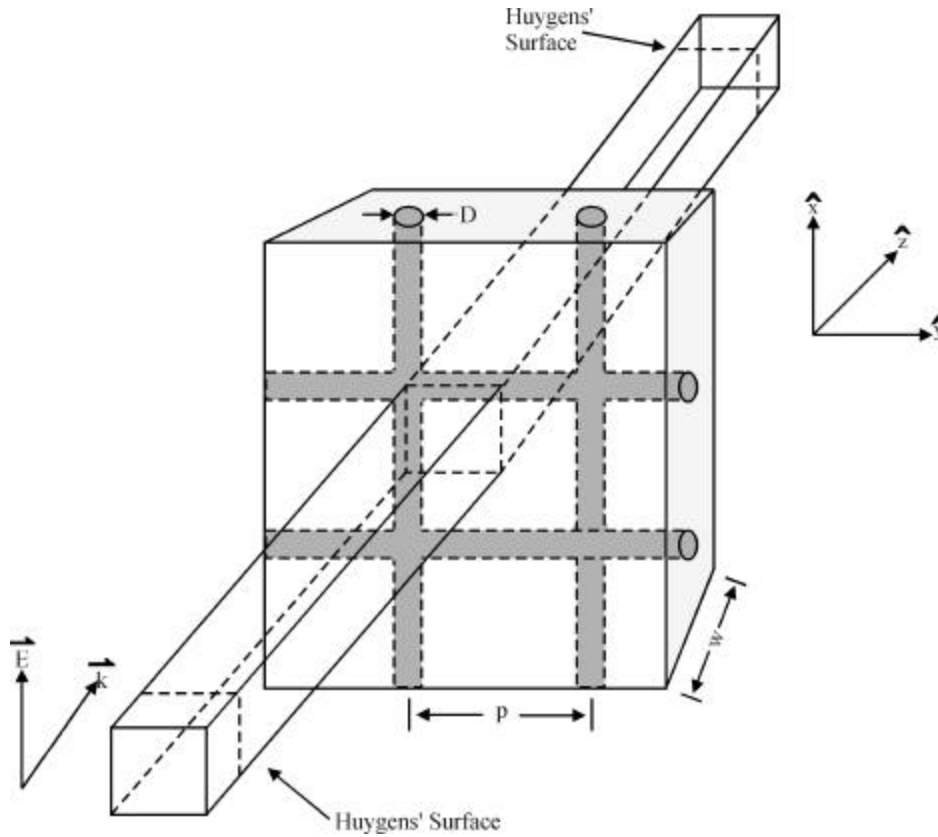


Figure A1. Reinforced concrete wall and FDTD computational volume.

In general, the FDTD technique requires the volume of the computational space (i.e., the reinforced concrete wall and the air region on either side of the wall) to be subdivided into unit rectangular parallelepiped cells. The algorithm is implemented using a staggered grid in both space and time [6-7]. For this calculation, the scattering object was included by setting the conductivity to 1.95 mS/m and the relative permittivity to 6 at cell locations occupied by the concrete wall and setting the tangential electric fields on the boundaries of the re-bar equal to zero. These electrical parameters are typical for concrete at 1 GHz.

A normally incident plane wave is introduced into the computational volume by using a numerical implementation of the electromagnetic equivalence principle. The equivalent electric and magnetic currents on a Huygens surface outside of the scattering object are set so as to produce the desired plane wave fields inside the surface (in the absence of the concrete wall) and zero field outside the surface. Thus when the scatterer is introduced, the numerical code produces the total field (incident + scattered) inside the surface and the scattered field outside of the surface. The electric field is aligned with one of the re-bar axes for these simulations. A time-domain pulse with a useful bandwidth that exceeded 6 GHz was used as the forcing function for the Huygens surface.

The size of the spatial increment is governed by two requirements. First, the finite difference grid needs to resolve the highest frequency of interest. This is usually accomplished by using at least 10 cells per wavelength at this frequency. Secondly, the cells need to be small enough to resolve all scattering objects in the computational volume (re-bar in the present case). For this calculation, sizing the finite difference cells to resolve the re-bar was the more restrictive condition.

For the cell sizes required to resolve the re-bar (on the order of millimeters), the computational volume must be kept as small as possible so as not to exceed computer resources. This is accomplished by exploiting the periodic structure of the concrete wall and using a normally incident plane wave polarized parallel to the re-bar. Under these conditions, symmetric boundary conditions are applied in two spatial directions and hence, two dimensions of the computational volume were reduced to half a period of the structure. Absorbing boundary conditions are applied on boundaries that are not planes of symmetry.

Figure A2 gives the transmission coefficient for a re-bar structure having a period of 15.24 cm (6"), re-bar diameter of 1.91 cm (3/4"), and wall thickness of 20.32 cm (8"). Below 250 MHz very little electric field is transmitted. For frequencies above 500 MHz there is a complicated resonance pattern; however, the average electric field attenuation is only on the order of 3-5 dB.

Two effects influence shielding: re-bar reflection and concrete wall transmission. First, lower frequency fields are reflected by the re-bar structure. If the wavelength is very large compared to the re-bar spacing, then the re-bar grid acts much like a solid shield (Faraday cage) allowing very little field penetration. As the wavelength decreases (frequency increases) and nears the dimension of the re-bar spacing, the field penetration increases. Full transmission occurs when the re-bar spacing is on the order of a

wavelength in the concrete, $I_{concrete} = p \cdot D$, where p and D are defined in Figure A1. For the parameters here this occurs around 890 MHz. Second, a lossless slab in air will have zero reflection when its thickness equals half the wavelength in the material. Thus, although the concrete slab will have some attenuation due to its conductivity, a transmission peak is expected to occur when $I_{concrete}/2 = W$. For the parameters here this occurs around 300 MHz. Thus, the first resonance near 300 MHz is due to the concrete slab thickness. The resonance is somewhat attenuated due to the re-bar shielding. The next resonance near 600 MHz is the second slab resonance. Above 900 MHz, the two effects combine in a complicated manner; however, the re-bar no longer provides significant shielding. The slight decrease in average transmission coefficient above 2 GHz is due to attenuation loss in the concrete.

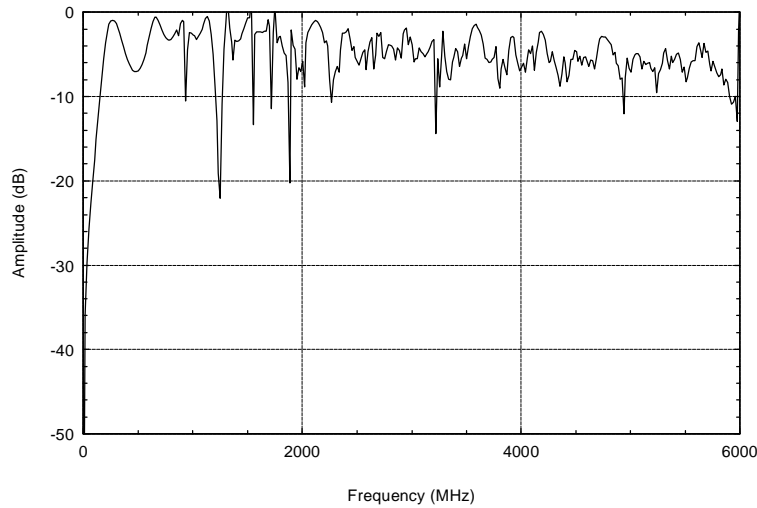


Figure A2. Transmission coefficients for a concrete wall with a 2 dimensional re-bar lattice: $P = 15.24$ cm, $D = 1.91$ cm, and $W = 20.32$ cm.

If the re-bar spacing is reduced, then the re-bar pass frequency will increase. Figure A3 shows results for the parameters as in Figure A2 but with the re-bar spacing halved to 7.62 cm (3"). The re-bar pass frequency will increase to approximately 2140 MHz ($I_{concrete} = p \cdot D$). The first local transmission peak in Figure A3 still occurs near the concrete wall pass frequency (300 MHz) but is still significantly attenuated by re-bar reflection (<10 dB). Further slab resonances occur near 800 MHz and 1300 MHz.

Increasing the re-bar thickness will improve shielding somewhat. Figure A4 shows the transmission coefficient for the Figure A2 parameters with the re-bar diameter increased to 5.08 cm (2"). This reduces the spacing to 10.16 cm (vs. 13.33 cm) and increases the re-bar pass frequency to approximately 1200 MHz (vs. 890 MHz). However, using thinner re-bar at a closer spacing is the more viable method to improve shielding.

The shielding effectiveness of reinforced concrete walls depends on the bandwidth and frequency of the potential RF fields, the particular wall structure, and electrical

properties. Changes in these variables can significantly alter the reflection and transmission properties of the structure. Hence, reflection and transmission properties based on single frequency measurements or calculations for a particular wall structure cannot be reliably extrapolated to predict the characteristics for similar structures with different physical dimensions or frequencies. The conclusion here is that the shielding effectiveness of a reinforced concrete structure is quite variable and cannot be reliably determined without a priori knowledge of the RF frequency and specific construction methods. In general, it should be assumed that building construction does not provide shielding from potential RF fields, particularly in the range 1-5 GHz.

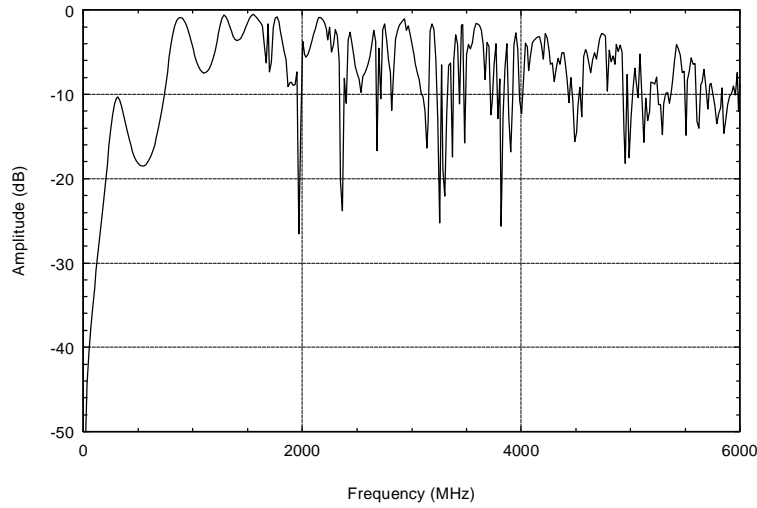


Figure A3. Transmission coefficients for a concrete wall with a 2 dimensional re-bar lattice: $P = 7.62$ cm, $D = 1.91$ cm, and $W = 20.32$ cm.

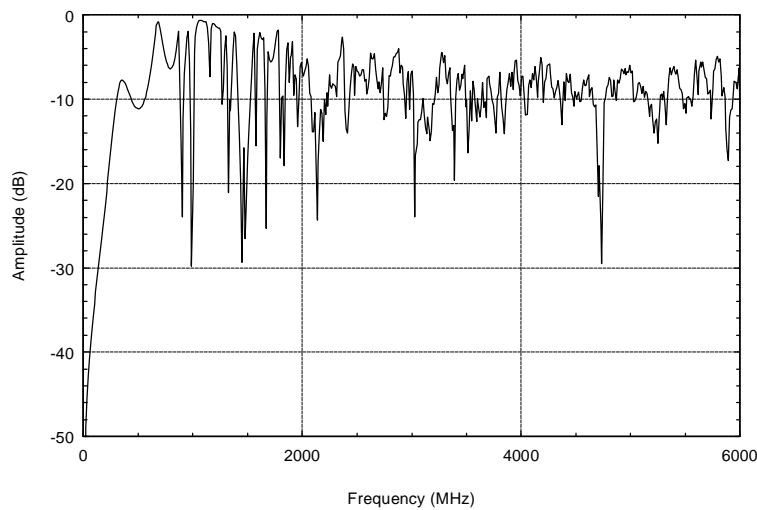


Figure A4. Transmission coefficients for a concrete wall with a 2 dimensional re-bar lattice: $P = 15.24$ cm, $D = 5.08$ cm, and $W = 20.32$ cm.